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Geiger Counters

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ABSTRACT

Three causes of delays in Geiger Counters are discussed, namely; electron transit time, time for the spread of the discharge along the wire, and the time for the outward motion of the positive ion sheath. Various experimenters are cited with the important details of their results and experimental procedures. A discussion of the long transit lags due to negative ions and of the distribution of delays is included.

INTRODUCTION

Of considerable interest in some applications of Geiger Counters is the "time-lag" -- the time between the entrance of an ionizing particle into the counter and the recording of a count by some external circuit. For example, in coincidence measurements in which the resolving time of the electronic circuit is smaller than the counter time-lag, there is a likelihood of the loss of true coincidences. Another example is the lifetime measurement of short-lived isotopes where the time-lag may be of the same order of magnitude as the lifetime to be measured. These Counter time-lags have been known for some time[1,2,3]. Values ranging from as low as 0.01 μsec. to as high as 100 μsec. have been reported.

In discussing the causes of these delays, it is well to consider the discharge mechanism of a Geiger Counter. We will begin with the entrance of an ionizing particle into the Counter and assume, for simplicity, that only one ion-pair is produced. Under the influence of the electric field of the Counter, the electron will drift towards the central wire and the high field region. In case the electron is "captured" to form a negative ion, there will be a much longer transit time because of the much lower mobility of negative ions. When the negative ion reaches the high field region, it will lose its electron and the process will continue in a similar manner as for a free electron. In the high field region, the electron will gain enough energy to ionize other atoms by collision and the well-known Townsend avalanche will take place. The time for this Townsend

avalanche will not be considered as a cause of delay since its magnitude is much smaller than the other delays involved[4]. During the Townsend avalanche, photons will be emitted by excited noble gas atoms returning to the ground state. These photons will produce new photo-electrons (either from an organic vapor, if present, or from the cathode if only a pure noble gas filling is used). These photo-electrons will propagate the discharge by means of new Townsend avalanches until the discharge has spread along the whole length of the wire. The second delay to be considered is thus the time required for the discharge to spread along the wire. As the discharge spreads along the wire, the electrons formed are collected almost immediately, leaving a positive ion sheath which surrounds the central wire. The major portion of these electrons is "held" on the wire by the electrostatic attraction of the positive ion sheath. As the positive ion sheath moves outward to the cathode, these electrons will leak off and the major portion of the negative pulse is formed. When low-sensitivity detectors are used, we must thus consider a third delay; the time required for the positive ion sheath to drift far enough from the central wire to permit formation of a large enough pulse to trigger our detector.

We may summarize the three causes of delays:

(a) The transit time of the electron formed in the initial ionizing event from its place of origin to the avalanche region.

(b) The time required for the discharge to spread along the length of the wire.

(c) The time required for the positive ion sheath to drift far enough from the central wire to permit formation of a large enough pulse to trigger our detector.

Delay (a) can never be eliminated although good counter design and operating conditions can minimize it. If no negative-ion forming gases are present, the long delays due to negative ions can presumably be avoided. However, with the current prominence of halogen counters, this factor must be considered. Delays (b) and (c) can be minimized (even eliminated) through the use of high-gain amplifiers of extremely fast rise-time which will aid in the detection of the small number of electrons which escape from the wire before the complete propagation of the ion sheath[5]. The spread time of the discharge can be limited by operating the counter in the proportional region (where, however, greater detection sensitivity is necessary). Another way of limiting the spread is the well-known method of spacing beads along the central wire as used by Stever[6] and others. Circuits which serve to limit the spread have also been developed by Simpson[7], Porter and Ramsey[8], and others.

TRANSIT LAG

Sherwin[9] measured (a), the transit lag, in an end-window counter containing 9.2 cm. of Argon and 0.8 cm. of Amyl-Acctate. Beta particles were introduced parallel to the axis as indicated in Figure 1. A slot, S, placed at different positions allowed the particles to enter Counter A at a known distance from the axis. The pulse from A was used to trigger the sweep of an oscilloscope. The pulse from the small counter B was delayed by a constant amount (0.65 sec.) and introduced to the vertical plates. Thus, assuming no lag in Counter B, an early appearance of the pulse from B would indicate a lag in A. High-gain wide-band amplifiers were used and a calculation indicated that the sheath spread was only 1 - 2 mm. at the time of detection. Distributions of the lags in A were obtained and some of the results are shown in Table I.

Table I

Sherwin's measurements of transit lags in an end-window counter.

Distance of S from axis. (mm.)	Lag Peak (μsec)	Transit time, 1 cm. to S. (μsec)
1.7	.06	.09
5.0	.09	.06
10.0	.15	0

The width of the distribution curves obtained by Sherwin were approximately the same for all three positions of S. This was attributed mostly to the fluctuations (delays) in counter B. Replacing B by a counter of much smaller size decreased these fluctuations (as expected) and cut the half-width of the distributions by greater than one-half.

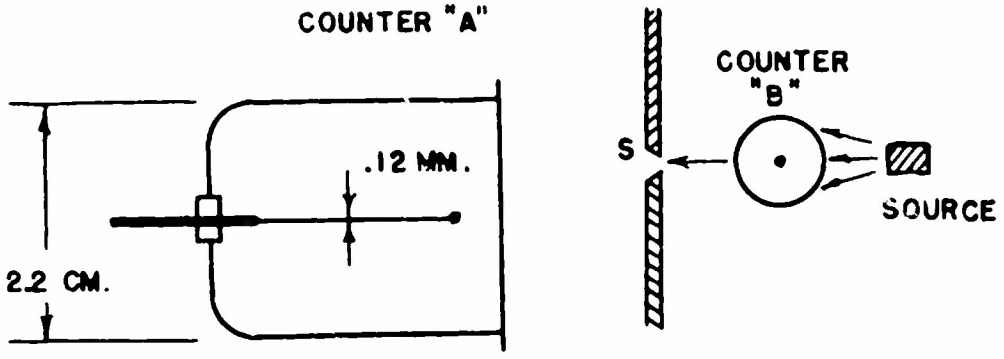

FIGURE 1 - SHERWIN'S EXPERIMENTAL SETUP FOR DETERMINATION OF TRANSIT LAGS.

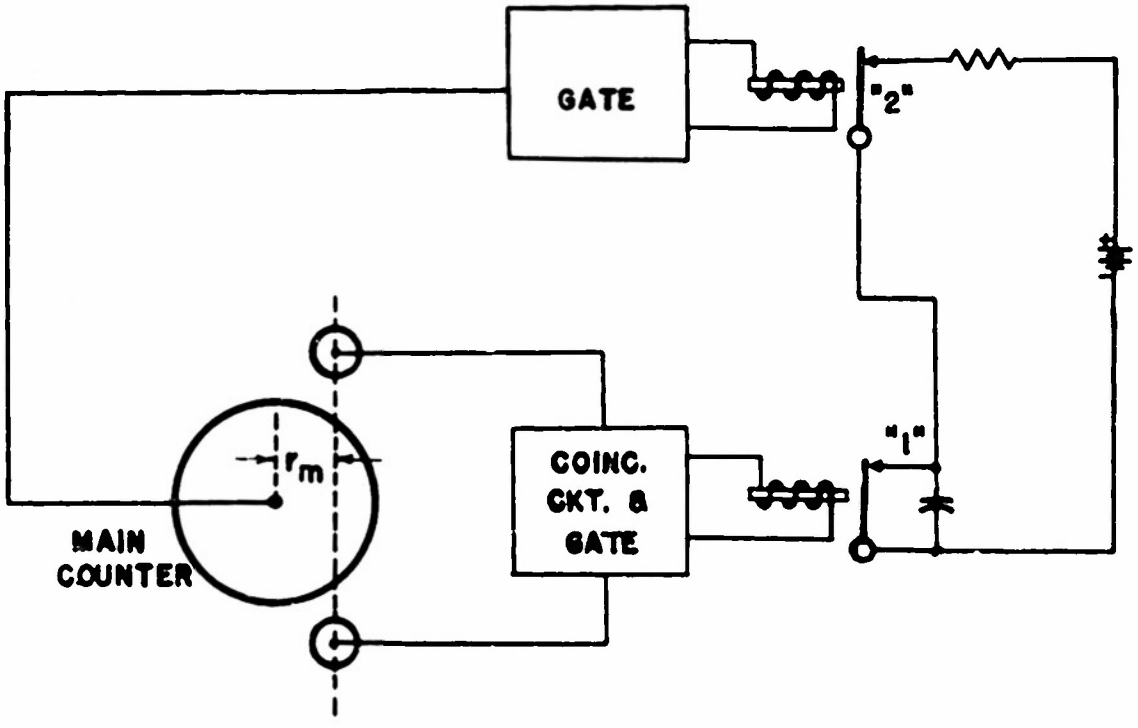

FIGURE 2 - DEN HARTOG, et. al., EXPERIMENTAL SETUP FOR DETERMINATION OF TRANSIT LAG.

j.a.

The position of the electrons as a function of time was computed from the average data of the distribution curves. These points appeared to fit a theoretical curve calculated on the assumption:

$$v = R\left(\frac{E}{P}\right)^{\frac{1}{2}} \text{ cm./sec., where } R = 4.5 \times 10^{6} \frac{\text{cm/sec}}{(\text{volts/cm.} - \text{mm. Hg})^{\frac{1}{2}}}$$

These transit times were also found to be independent of overvoltage from threshold (1050 volts) to 300 volts overvoltage.

One of the defects of Sherwin's experiments was that he measured a "relative lag" between two counters. Another bad factor was the inexactness of the place of origin of the initial electrons. This is minimized by using a small source, a very narrow slit, and placing the slit close to the counter.

Den Hartog, Muller, and Vester[10] measured the time lag in a 7 cm. diameter (.05 mm central wire) counter filled with 9 cm. of Argon and 1 cm. of alcohol. They used a chronoscope arrangement as indicated in Figure 2. The two smaller counters served to define incident cosmic rays within a narrow region. Again we have the defect of the measurement of a "relative lag". There is again the inexactness of the place of origin of the initial electrons.

A coincidence count of the two smaller counters would cause gate "1" to open and allow the condenser to begin charging. When the main counter discharges, a gate circuit opens "2" preventing further charging of the condenser. The voltage attained will be proportional to the time-lag and is measured by Y-axis deflection of an oscilloscope beam. A correction factor (due to delays of the small counters and differences in the two

channels) of 0.22 μsec. was calculated. No delays below this value were observable. In a later experiment[11], a constant delay was placed in one channel to eliminate the necessity for this correction factor.

The small counters were 1.2 cm. in diameter. The peak and the extent of the time-lag distributions is shown in Table II.

Table II

Transit lag measurements of Den Hartog, et. al. (at 180 v. overvoltage)

r_m (distance from wire - mm.)	Lag Peak (μsec)	Shortest Lag (μsec)	Longest Lag (μsec)
34	1.9	0.3	2.2
29	1.75	0.3	2.1
26	1.1	0.22*	1.7
23	0.92	0.22*	1.5
17	0.4	0.22*	1.0

*0.22 sec., lowest lag observable.

A graph of root-mean-square time-lag versus distance from the axis indicated a direct relationship between the electron velocity and the field (time lag was proportional to the radius squared),

$$v = k_2 \left(\frac{E}{p}\right),$$

where for the particular mixture used, $k_2 = 1.57 \times 10^6 \frac{\text{cm/sec.}}{(\text{volts/cm.} - \text{mm Hg})}$ and E/p varies from 0.6 to 2 volts/cm. per mm. Hg. This relation is in contrast to Sherwin's value of v proportional to $(E/p)^{\frac{1}{2}}$. Comparison of the data shows that all of Sherwin's measurements were made relatively close to the axis in the high-field regions, while Den Hartog, et. al. made measurements in the low-field regions. We shall see later that this is consistent with the results of other experimenters.

Laufer[12] made systematic measurements of transit time-lags as functions of various counter parameters. He used a 2.5 cm. diameter counter (4 mil wire) equipped with quartz windows and several holes drilled along the cathode wall (see Figure 3). Light from a fast spark was admitted to each hole through a quartz window and initiated a count by ejecting photoelectrons from the far wall. The holes were distributed along the cathode so as to avoid the delay due to sheath propagation along the wire. The spark was detected by a phototube and the phototube pulse used to start the sweep of a fast synchroscope. The time interval between the phototube pulse and the appearance of the Geiger pulse was taken to be the "absolute lag". Constant delays were used to enable both pulses to be conveniently viewed. A summary of Laufer's results is given in Table III.

In Laufer's procedure, we see two major improvements over the experiments previously described. Laufer measured an "absolute lag". In addition, the point of origin of the original electron is exactly determined (the cathode).

Laufer's results show a tendency of the transit lag to increase with total pressure and that it is approximately independent of overvoltage. There is a slight tendency towards higher lag with increasing percentage of organic vapor.

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TABLE III

Laufer's Time-Lag Measurements

FILLING		TOTAL PRESSURE (cm. Hg)	OVERVOLTAGE (volts)	AVERAGE TRANSIT LAG (electrons) (μsec)	AVERAGE TOTAL LAG (μsec)
Argon-Ethyl Alcohol	90%-10%	varied from 6 - 20	100	varied from 0.24 - 0.39	varied from 0.39 - 0.70
	varied 95%-5% to 70%-30%	10	100	approx. 0.27 (slight decreasing tendency)	varied from 0.54 - 0.45
	90%-10%	10	varied 40 - 200	approx. 0.28	varied from 1.16 - 0.55
Argon-Amyl Acetate	90%-10%	varied from 6 - 20	100	varied from 0.25 - 0.36	varied from 0.46 - 0.76
	varied 95%-5% to 70%-30%	10	100	approx. 0.28 (slight decreasing tendency)	varied from 0.58 - 0.53
	90%-10%	10	varied 40 - 200	approx. 0.29	varied from 1.54 - 0.57
Hydrogen		varied from 4 - 20	100	varied from 0.22 - 0.36	varied from 0.23 - 0.42
		10	varied 40 - 200	approx. 0.28 (slight decreasing tendency)	varied from 0.43 - 0.29
Argon-Oxygen	varied 95%-5% to 0-100%	10	100	approx. 0.14	approx. 0.28
	90%-10%	10	varied 40 - 200	approx. 0.14	varied from 0.78 - 0.19
Oxygen		varied from 4 - 12	100	approx. 0.13 (slight increasing tendency)	varied from 0.16 - 0.29
		10	varied 40 - 200	approx. 0.13	varied from 0.60 - 0.17

FIGURE 3
LAUFER'S QUARTZ-WINDOW COUNTER

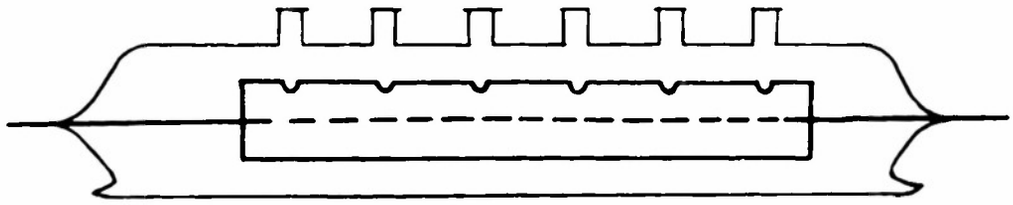
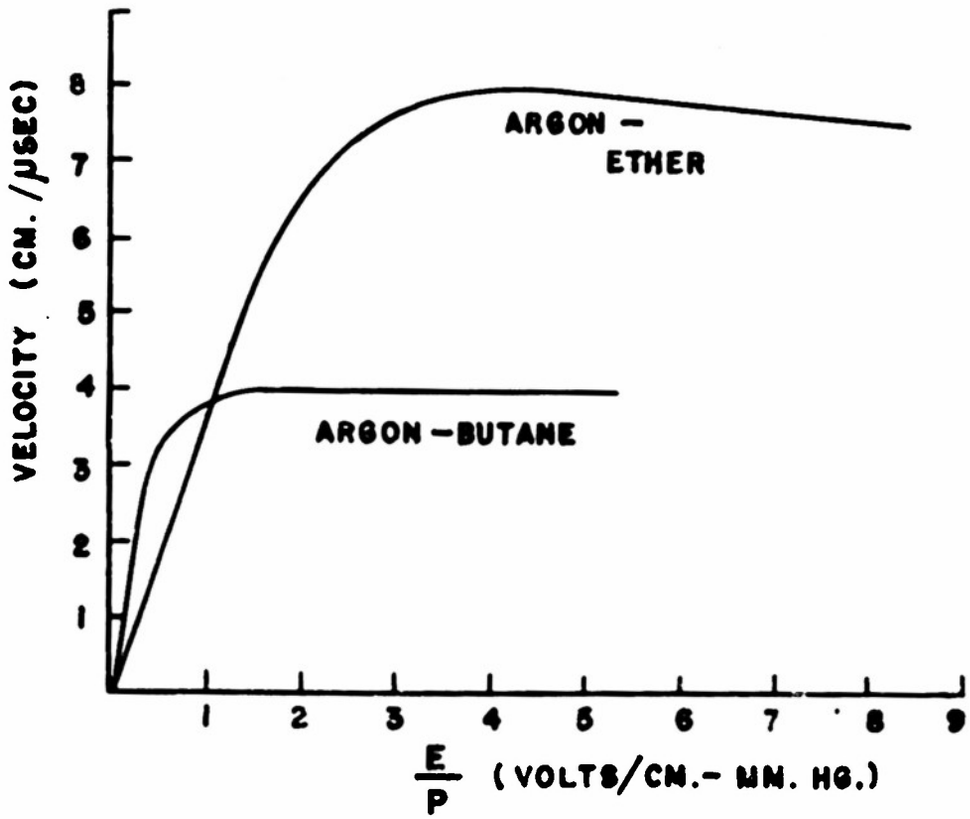


FIGURE 4 — STEVENSON'S VALUES OF ELECTRON VELOCITY IN GEIGER COUNTER MIXTURES.



Assuming a constant mobility of electrons at any given pressure, thus a $v = k E$ law, Laufer computed the mobilities on the basis of his measured transit times. He found that they showed a decrease with both increasing pressure and increasing percentage of organic vapor or oxygen. The values of mobility found for argon-organic vapor mixtures are higher than those for pure argon alone. This result is also found by Den Hartog, et. al.[10] and is explained as due to the decrease of Ramsauer cross-section (hence higher mobility) for the electrons slowed down by inelastic collisions with alcohol molecules. Den Hartog, et. al.[11] obtain an increasing linear relation between $1/k$ and % alcohol (above 6%). They indicate, that for the range considered, the effective cross-section of argon is negligible and thus the drift velocity is governed mostly by the alcohol.

Some more recent measurements of electron velocities in Geiger counter mixtures (although not in an actual Geiger counter) have been made by Stevenson[13]. His results are shown in Figure 4. The electron velocity first follows a $v = k (E/p)$ relation; then at higher E/p, a $v = k (E/p)^{\frac{1}{2}}$; and finally for sufficiently high fields, it levels off. This leveling-off is also found for argon-nitrogen[14] and argon-carbon dioxide mixtures[15]. The varied (E/p) dependence was previously seen in a comparison of the work of Sherwin and Den Hartog, et. al. (see page 6).

We see that the problem of computing the transit time of an electron in a counter will be quite complicated due to this varying dependence of the velocity in different field regions. There is also the serious factor

of the considerable effect on mobilities of even small amounts of impurities and an accurate calculation may be too much to expect. Porter and Ramsey[16] did get a 10% agreement between measured and calculated maximum transit delays in a small argon-ether counter operated so that v was approximately constant over most of the path (operation at high E/p).

SPREAD OF THE DISCHARGE ALONG THE WIRE

The mechanism of discharge spread takes different forms for counters containing pure gases or vapor admixtures. In the former, photons are emitted by excited pure gas atoms returning to the ground state. These eject photo-electrons from the cathode which travel to the wire and start new avalanches at different places[17]. If an organic vapor (e.g. alcohol) is present, the photons will be energetic enough to photo-ionize the organic molecules[18]. The liberated electrons make the relatively short trip to the wire, forming new avalanches and propagating the discharge close to the wire.

The theoretical calculation os the sheath spread velocity has not been definitely resolved. Two methods, neither of which is entirely satisfactory, have been proposed. Wilkinson[19] computes the velocity on the basis of a "constant burning length" which propagates along the wire with a constant speed. He offers only one value as a check[20]. Alder, et. al. take the more straight-foreward approach of considering the mean-free-path of photon travel and the transit time of new photo-electrons formed from alcohol atoms. Their agreement with experiment seems doubtful. An essential part of their theory is the determination of three constants from experimental data. Thus, their approximate agreement is possibly accidental. Both theories have been previously compared by Den Hartog[22].

One assumption made by both (although not completely essential to either theory), is that the governing factor in the propagation velocity is the transit time of the photo-electron from its birth to the wire. They consider the excitation lifetime of the argon atoms as negligible. Alder, et. al. quote a value of 2×10^{-10} seconds which they say is obtained from radiation damping (no further reference is given). Wilkinson assumes the same value. Most references list excitation lifetimes of representative atoms as of the order of 10^{-8} to 10^{-9} seconds[23,24,25]. This is larger than the usually assumed transit time of the photoelectrons of 10^{-9} seconds and thus forms a considerable part of the propagation delay. Other references concerning the spread mechanism are available[26-32].

The velocity of propagation has been measured by several experimenters. A typical method of measurement is to determine the difference in the time of discharge of two small segments of counters placed at the ends of a large counter. The discharge is initiated at one end.

One of the main results is an approximately linear relation between the velocity of propagation and overvoltage[19,21] (see Figure 5). Miss J. Freeman's results quoted by Wilkinson[32] indicate velocities ranging from about 2 to 7 cm/μsec. for overvoltages up to 80 volts. Wantuch's[33] measurements of spread velocities in argon-ethyl alcohol counters were about 50% lower than those shown in Figure 5 and agree more closely with Miss Freeman's values.

FIGURE 5 – ALDER, BALDINGER, HUBER, METZGER – SHEATH-SPREAD VELOCITY

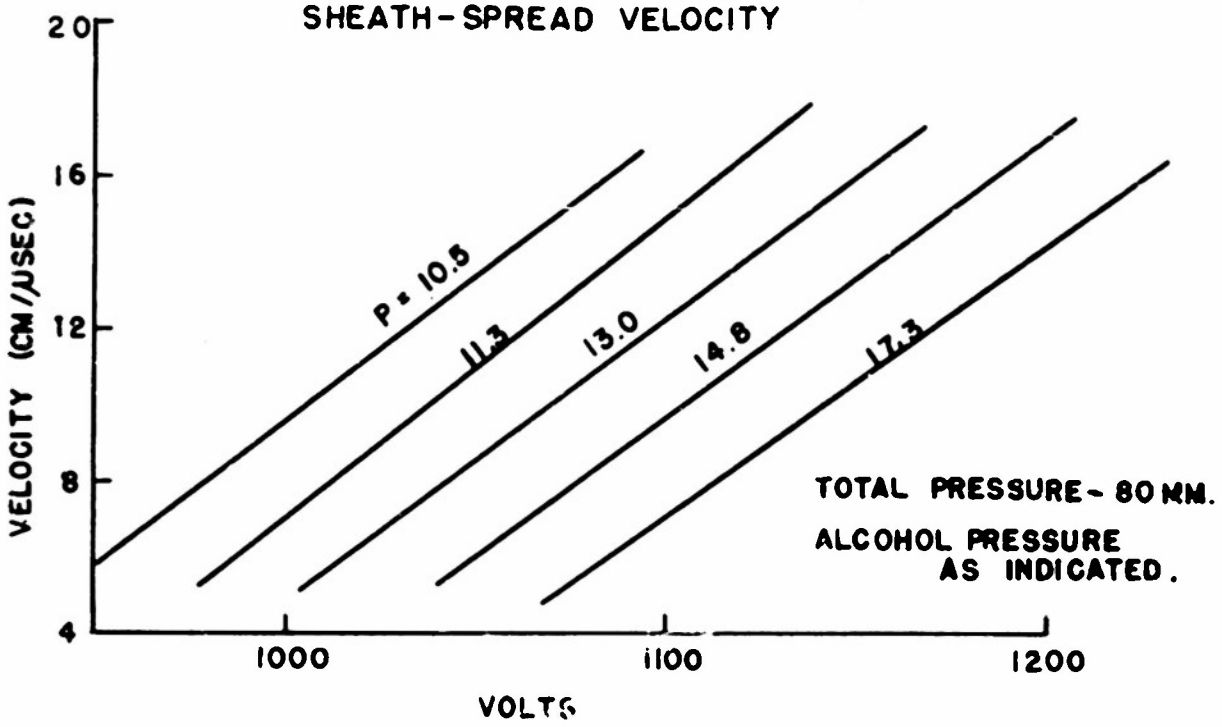


FIGURE 6 – LAUFER, SHEATH SPREAD VELOCITY

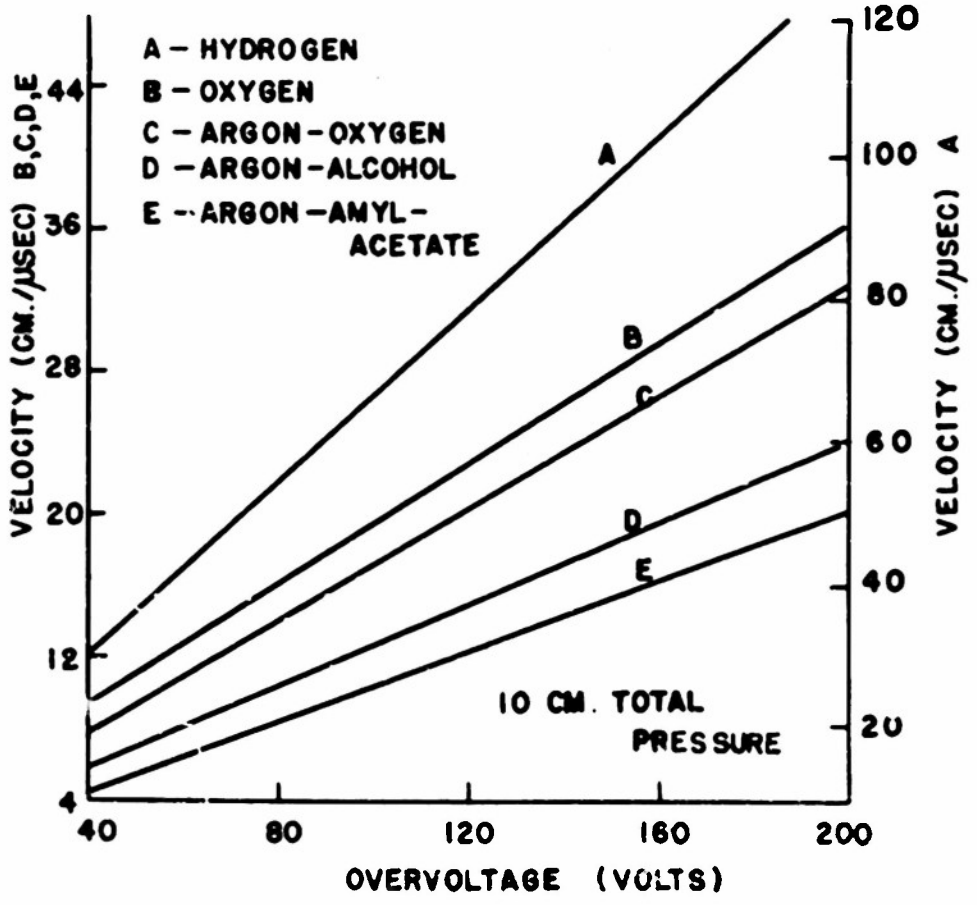


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FIGURE 7 — LAUFER,
SHEATH SPREAD VELOCITY

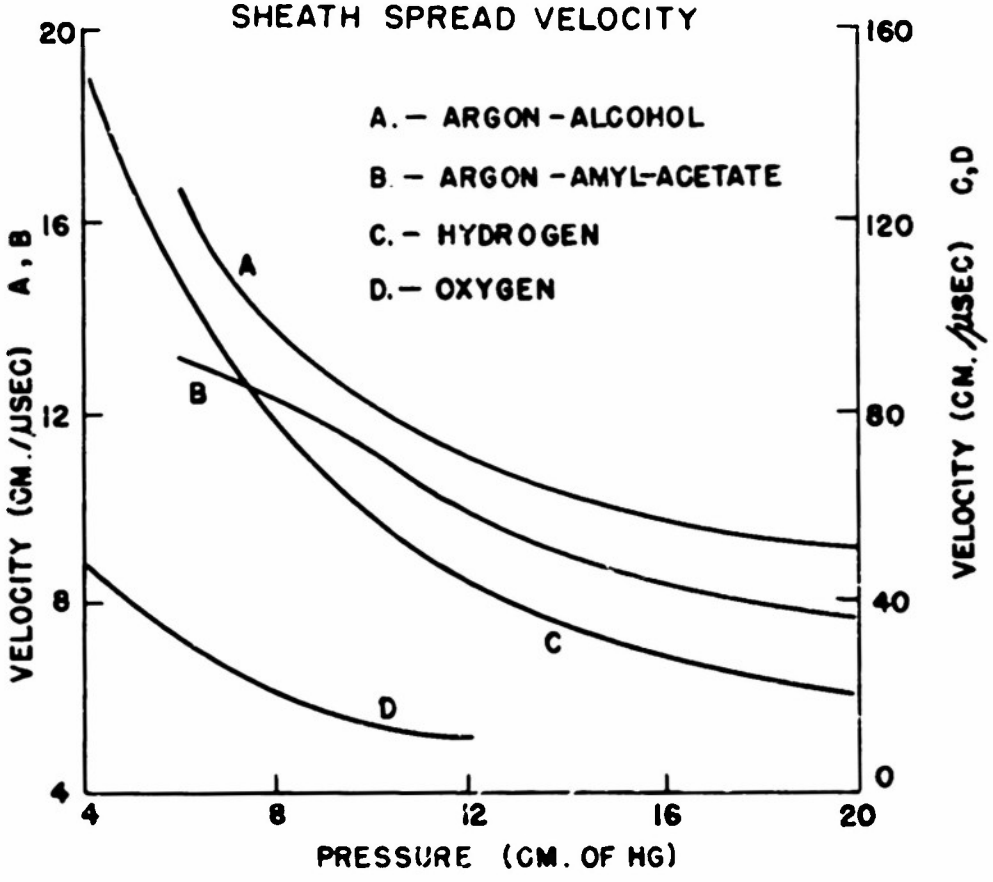
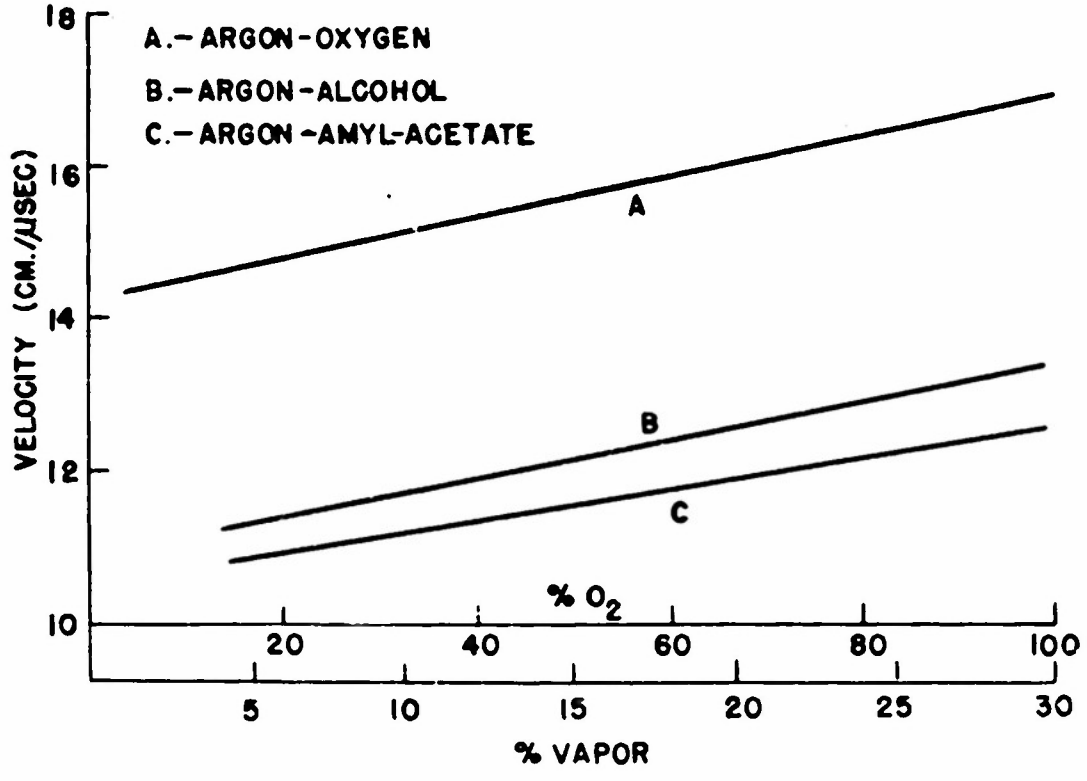


FIGURE 8 — LAUFER, SHEATH SPREAD VELOCITY



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Laufer[12] measured a total lag in a similar manner as the transit lag (see previous discussion), In this case, he covered all but one of the quartz windows so that the discharge started at only one spot. The difference between the total lag and the transit lag was attributed to a "sheath lag" - the time required for the sheath propagation along the wire and for the sheath to travel far enough out from the wire to permit a detectable pulse. (The sheath propagation and outward spread are simultaneou events, i.e. part of the sheath begins to move outward while the rest is still forming). Laufer derives a formula for the fractional pulse size, considering both the propagation velocity and the outward motion of the sheath (assuming constant ion mobility). Using his "sheath lag" data, he then can calculate the velocity of propagation along the wire (making use, of course, of his particular detection sensitivity). His data is summarized in Table III and Figures 6,7, and 8.

Again we see that the velocity increases linearly with overvoltage. This is explained as due to the higher electron velocity in the higher field. However, we have seen previously for high fields that the velocity becomes constant in typical Geiger counter mixtures. This also neglects the excitation lifetime which should play an important role here. Thus, while all experiments indicate a linear dependance of spread velocity on overvoltage, the explanation is still somewhat in doubt.

The decrease of spread velocity with total pressure (Figure 7) is explained as due to a decrease in the "mean-free-path" of the photons.

Thus the distance between avalanches is smaller and the entire propagation takes a longer time.

Although electron mobility decreases with added percentage of alcohol, a higher operating voltage is required to get the same overvoltage as at lower percentages of alcohol, This probably results in an increased electron velocity and this apparently overshadows the tendency of the mobility to decrease (see Figure 8). This explanation by Laufer is based on an increase of electron velocity with field. As we have seen, this may not be true in the field regions considered here.

OUTWARD MOTION OF THE SHEATH

The outward velocity of the positive ion sheath is governed by the mobility of the positive ions in the mixture. As mentioned previously, Laufer assumed a constant mobility. This is consistent with the measurements of Den Hartog and Muller[34]. The delay due to the outward motion can be minimized (practically eliminated) by utilizing an amplifier of sufficiently high gain and wide band width. The profound effect of the outward motion is on the "dead-time" - the natural insensitive time. A discussion of this phenomenon is not within the scope of this report.

NEGATIVE IONS

Long transit delays will occur in counters containing electro-negative gases. Here there is a finite probability that all of the electrons formed in the initial ionizing event will be captured and proceed to the wire as negative ions (which have a much lower mobility than electrons). These delays should be considerably longer than those previously discussed. In case only some of the original electrons are captured, those not captured will proceed to the wire as usual and the usual delay due to electron transit will apply. The negative ions will arrive at a later time and may cause spurious counts. A discussion of spurious counts is not within the scope of this paper.

Rose and Ramsey[35] used a similar experimental set-up as Den Hartog, et. al. (see page 5) to measure the efficiency of pure oxygen and argon-oxygen filled counters as a function of resolving time of the external circuit. The capture probability in the pure oxygen counters was high. A considerable decrease in efficiency was found for low resolving times (less than 30 μsec.). This would indicate a number of "lost counts" due to long lags in electro-negative oxygen. The efficiency was found to be lowest when the initial ionizing particle was introduced close to the cathode where the trip to the central wire was longest and the capture probability therefore greatest.

The Montgomerys, et. al.[1] measured delays of the order of 1.5 to

2.8 μsec. in counters containing oxygen. In a later experiment[36], they used the spark-method to measure delays in a counter filled with a 94-6% argon-oxygen mixture. (This was the same method, later used by Laufer, described previously in this paper.)

The Montgomerys used a weak intensity of spark illumination and made the following analysis. If an average of "n" electrons is ejected by a spark, e^{-n} is the probability that no electron will be ejected, and:

$$\beta = 1 - e^{-n}$$

is the ratio of the number of counter discharges to the number of sparks. (This assumes that only one electron is necessary to cause a counter discharge as is normally the case). The probability of the ejection of "m" electrons is given by:

$$P_m = \frac{e^{-n} n^m}{m!}$$

For a long delayed count, all of the electrons must be captured. Denoting the capture probability by α, the probability P_α that a spark will produce a long delayed count is given by:

$$P_\alpha = \sum_{m=1}^{\infty} \alpha_m P_m$$

Substituting the previously designated expression for P_m, this can be summed to give:

$$P_\alpha = e^{-n}\left(e^{\alpha n} - 1\right)$$

Both P_α and β can be measured directly. The Montgomerys measured both for three minimum time-lag settings as a function of pressure. From these results, they calculated α, the capture probability. There values are shown in Figure 9.

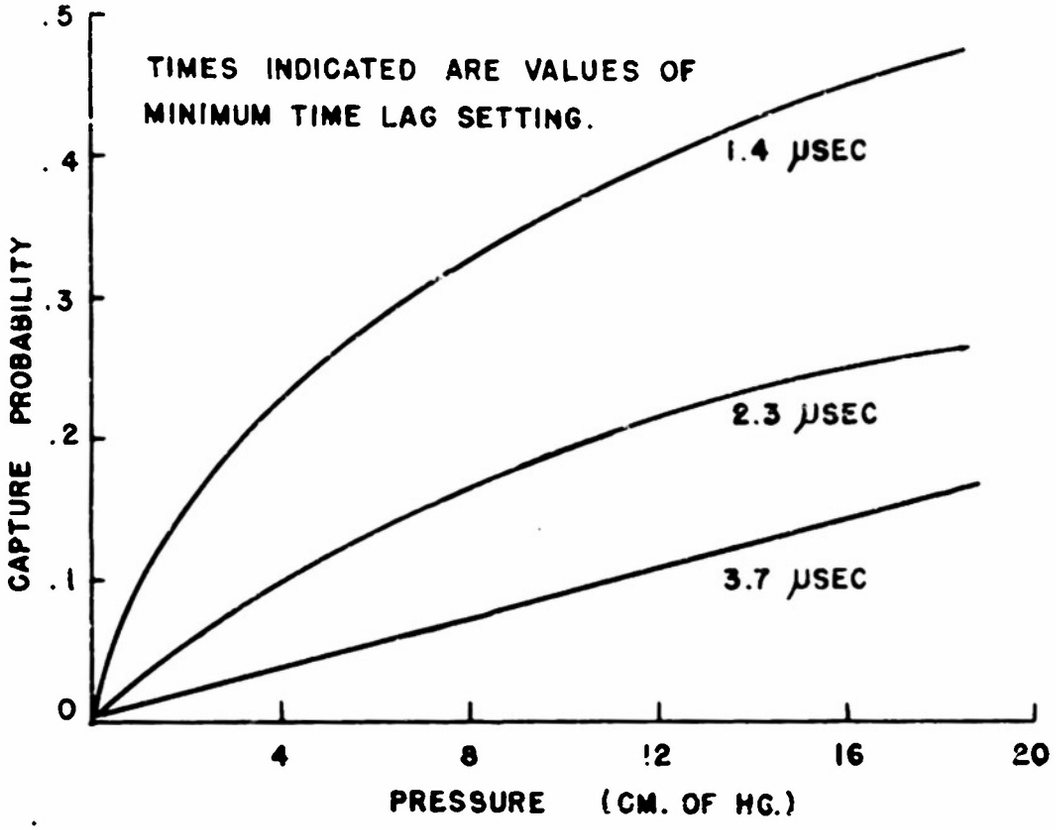
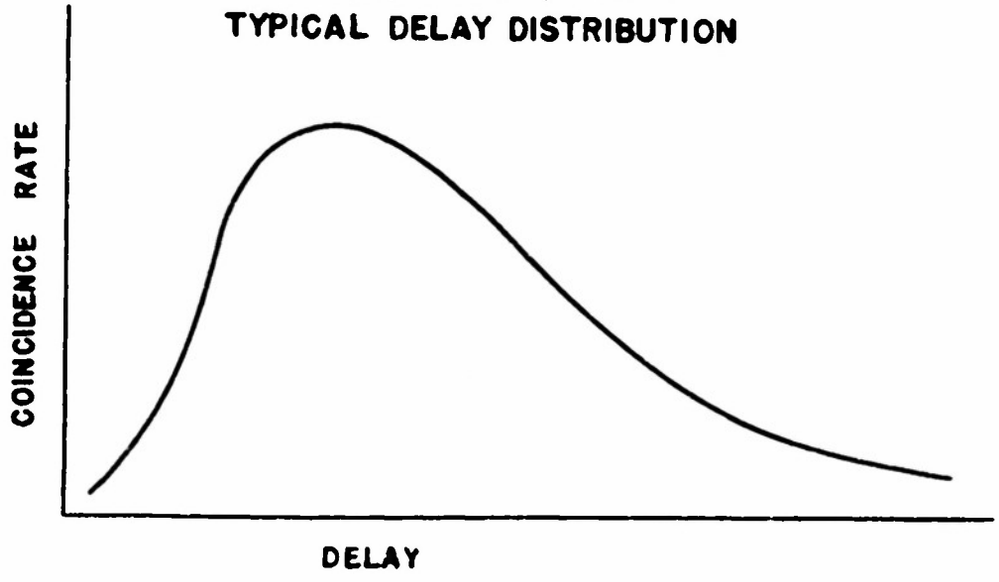


FIGURE 9 – MONTGOMERY & MONTGOMERY, CAPTURE PROBABILITIES

FIGURE 10

BUNYAN, LUNDBY, WALKER
TYPICAL DELAY DISTRIBUTION



Mandeville and Scherb[37] found no loss in coincidences in small argon-ether counters for resolving times as low as 0.08 μsec. This would indicate that no appreciable number of negative ions are formed in such counters.

Loosemore and Sharpe[38] measured delays ranging from 3 to 9 μsec. in counters containing bromine, an electro-negative gas (as are all of the halogens).

In his experiments with counters containing oxygen, Laufer[12] noted a number of lags greater than 5 μsec. He attributed all of these lags to the formation of negative ions by capture. A summary of his results is given in Table IV.

TABLE IV

Laufer's Long Transit Lags

Filling	Proportions	Total Pressure (cm. Hg)	Overvoltage (volts)	% of lags > 5 μsec.
Argon-Oxygen	varied 95% - 5% to 0 - 100%	10	100	varied 1.5% - 27.6%
	90% - 10%	10	varied 40 - 200	approx. 3.4%
Oxygen	100%	varied 4 - 12	100	varied 10.2% - 30.7%
	100%	10	varied 40 - 200	approx. 27%

From this data is seen the obvious increase in negative ion counts with added oxygen. Laufer also computed the capture probability as a function of oxygen pressure. He obtained curves similar to those previously obtained by the Montgomerys (see Figure 9).

Kitchen[39] used a method similar to Laufer's and found some long lags (greater than 5 μsec.) in counters containing several types of typical filling gases. He studied both pure vapors and mixtures. Long lags were also found in gases where the capture probability was very small. He showed that it was unlikely that these long lags were due to electro-negative impurities and attributed them to the formation of negative ions by dissociation near the avalanche region.

TIME - LAG DISTRIBUTIONS

Most of the experiments previously described have been concerned with the measurement of some definite delay. However, various factors will cause the actual delays to be distributed about some mean value. In applying corrections for counter lags, it is important to know the form of the distribution. Little work has been done in determining distributions although the problem has been considered by several workers using Geiger counters in delayed-coincidence set-ups.

In his experiment to measure the half-life of ThC' using a coincidence method, Van Name[40] simplified his calculations by assuming a triangular distribution of delays which yielded satisfactory results. Binder[41] extended Van Name's analysis using the more usual Gaussian distribution. Bradt and Scherrer[42] also measured the half-life of ThC' and obtained satisfactory results assuming a Gaussian distribution of delays.

Bunyan, et. al.[43] found a slightly asymmetric distribution as indicated in Figure 10. A detailed discussion of this has been made by Lundby[44]. He also indicates experimental justification for his calculated results. Another theoretical calculation by Nag, et. al.[45] also indicates such an asymmetric distribution.

Recently, Heirtzler of our Laboratory has made distribution measurements in counters containing various fillings. These will be reported in the near future.

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